ENERGY RELEASE IN SOLAR FLARES BASED ON OSO-5 DATA

under the direction of

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I. Outline of Proposed Program

It is generally agreed that energy released in a solar flare is derived from magnetic fields and that a large fraction of this energy goes into accelerating particles. Most of the observed radiation we receive is a product of the interaction of these particles with coronal and chromospheric plasma. Thus the determination of location and mechanism of particle acceleration is essential for the understanding of solar flares. Although some progress in gross features of acceleration has been made, the details are all a matter of considerable speculation.

In order to obtain further insight into the acceleration problem, we have come to the view that it is desirable to examine a small number of flares in great detail. Our aim is to accumulate, for each flare, as much observational data as possible. For each type of radiation, we would then hope to estimate the particle flux which must have been produced to cause this radiation. In this way, we would hopefully arrive at estimates of particle fluxes produced at various stages in the evolution of the flare. If such an analysis were carried through for a number of flares, the resulting information should show whether two or more phases of acceleration (as proposed e.g. by de Jager, 1969) are required to explain the overall properties of flares and it should also show what the main features of each phase of acceleration appear to be.

In this study, we propose to draw upon observational data, especially x-ray data, obtained by experiments on board the OSO-5 spacecraft. In addition, we are obtaining information from other spacecraft and ground-based observatories. For each flare, we shall check to see whether a gamma-ray event was registered by the Vela spacecraft. We shall also examine the particle-event catalog compiled by Van Hollebeke, Wang and McDonald (1974). We shall also obtain magnetograms, Hα patrol records and radio data from ground-based observatories.

Briefly: Direct observation of particles at the orbit of earth give information about the flux and spectrum of particles escaping the corona. Gamma-ray data will give information about the acceleration of ions. The hard x-ray data provides the most direct information about the accelerated electrons, in particular when interpreted in terms of the thick target model, such as that developed at Stanford (Petrosian, 1973). With this interpretation the hard x-ray data provides good estimates of the electron flux and spectrum as a function of time, independent of other parameters such as plasma density, magnetic field, etc. The soft x-ray observations provide information on the total energy content and evolution of the quasi-thermal flare plasma which may manifest the major fraction of the flare energy. The most important parameter which can be derived from the x-ray observations is the total energy content of the plasma.

Combining this with the spectral information from hard x-ray data, it is possible to estimate the low-energy cutoff of the electron spectrum, an important parameter for understanding the acceleration mechanism. The XUV data provide further information concerning the flare plasma, and UV data may provide information concerning the state of the transition region during a flare. Since all radio emission is ascribed to high-energy particles, radio observations are especially valuable. For example, microwave bursts with a temporal structure similar to that of the hard x-ray bursts are believed to be due to gyrosynchrotron radiation and provide information about the high-energy tail of the electron spectrum. Similar information can be obtained from most Type IV bursts, but these estimates are unfortunately sensitive to assumptions concerning the magnetic field.

II. Work in Progress

a) Analysis of November 5, 1970 Event

We have selected the November 5, 1970 event as the first candidate for this analysis. This event was chosen because of its high strength in hard x-ray data and because of the availability of data on particle events associated with this flare. In addition to the acquisition of x-ray data from OSO-5, we have requested optical, UV, radio and other x-ray data concerning this event from various observatories. We have received some information and are waiting for data from a few other sources. We have the following data in digital form: hard and soft x-rays from OSO-5, EUV and particle energy spectrum. In addition we have figures of microwave and meterwave radio emission and photographs of Hα which allow the flare to be identified. Most of these data require extensive deciphering and manipulation. This analysis is in progress. The hard x-ray data, on the other hand, is simple to analyze. Consequently we have made progress in the analysis of the hard x-ray data with regard to spectrum and temporal evolution of the flare.

This event has one additional interesting feature. Frost's (1969) earlier analysis of this event indicates the presence of 26 sec oscillations in the 55-82 keV channel during the first few minutes of the impulsive phase. Confirmation of such oscillations, their magnitude, and in particular the presence or absence of oscillation in other energy ranges, are very important for models of hard x-ray production. Consequently we are spectral-analyzing the data using the maximum-entropy method, which has resolving power and signal-to-noise ratios superior to other spectral estimations, particularly for short data samples. The results of this analysis for a period of 95 sec around 0321 UT of three channels are shown in Figure 1, which shows sharp peaks at a period of about 27 seconds, and what appears to be a series of harmonics. The presence of the 27 sec oscillation is not so clearly evident at other time intervals. As pointed out by Frost, when interpreting the results, the method of data collection must be considered. The measurements were collected from the rotating wheel of the OSO-5 spacecraft by sampling the solar burst for 0.19 secs during every period of revolution of 1.91 secs. It is therefore possible that beats are occurring between shorter periods ($\sim$ 2 sec or 0.19 sec) and the sampling periods. The harmonic structure would enable us to distinguish between the latter two possibilities.

We are in the process of refining this analysis and repeating it for the other channels and other time intervals in order to see whether such oscillations occur simultaneously in all channels, and if so what are the relative amplitudes in the different channels.

Such modulation of hard x-ray fluxes can be due either to modulation of the accelerated electron flux during acceleration or to modulation during the radiation phase. Coherent oscillation between mirror points of bunches of particles trapped in a magnetic bottle rooted in the chromosphere may explain the observed periodic modulation of the hard x-ray flux. In this model particles will radiate mainly near their mirror points where the electron density is high. We have begun investigation of this problem. In this calculation we will also determine the extent of beaming (toward the chromosphere) of the electrons responsible for the hard x-ray emission. Beaming of the electrons forms the basis for the model described by Petrosian (1973), which agrees with all aspects of hard x-ray observation (Petrosian, 1975).

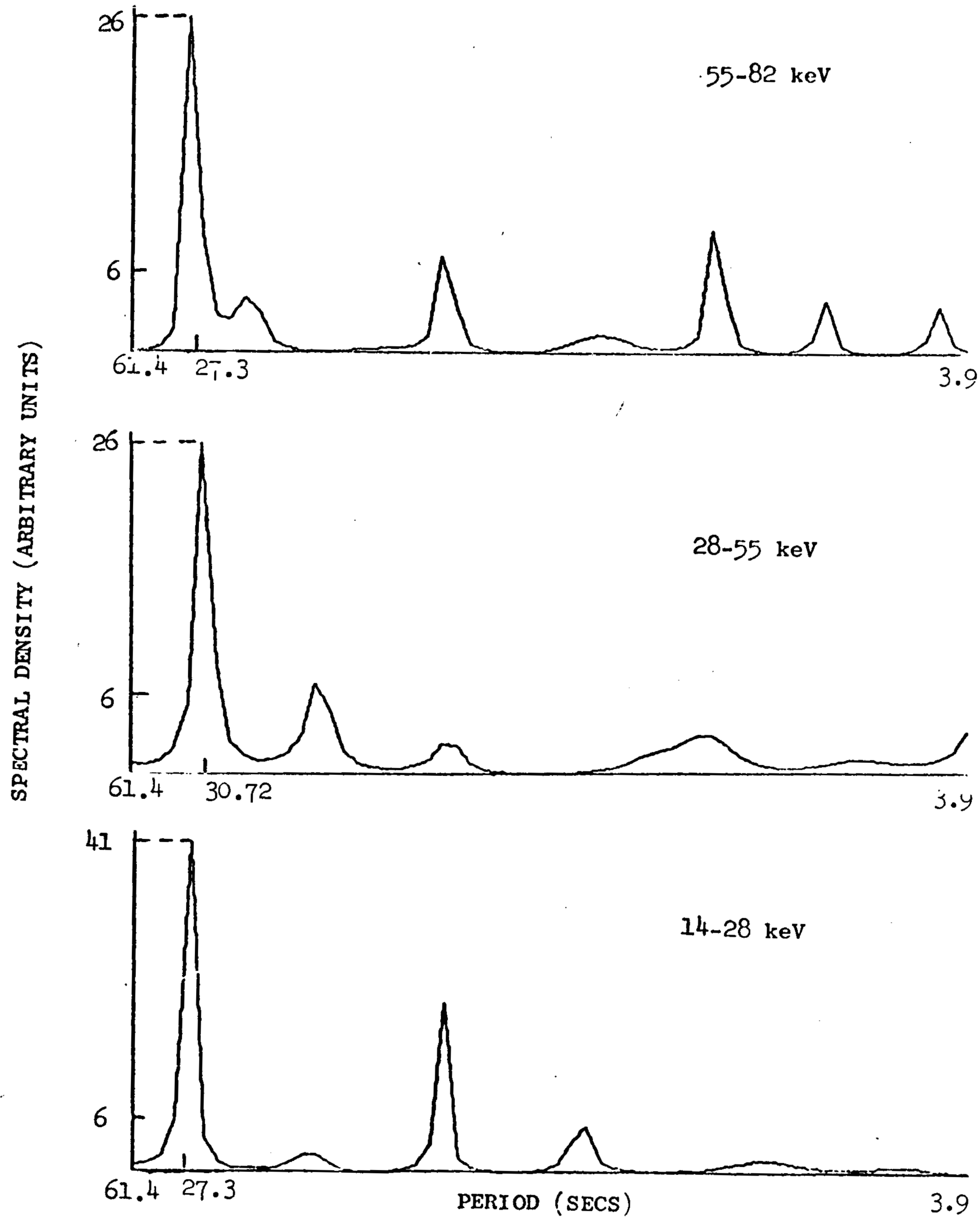

Figure 1. Maximum entropy power spectra, scaled by (signal standard deviation)^2. Samples of length 95 seconds were taken with a central time of 0321 UT. The maximum spectral density is given at the top left of each spectrum. The noise level is approximately 6 units.

Another explanation of this modulation is suggested by the betatron model of Brown and Hoyng (1974). We shall also investigate this possibility, and in particular shall determine if such short periods could be achieved by this mechanism. If the real period of the modulation turns out to be 2 or 0.2 seconds, this model can be ruled out.

b) X-Ray Albedo of Stellar Atmosphere

In general the x-rays produced during a flare will not be omnidirectional. Part of the radiation observed at the earth will be due to the direct flux but there will also be a component that is diffusely reflected from the photosphere. This reflected component has been analyzed in other contexts and may contain up to 30% of the flux incident on the photosphere (Santangelo et al., 1973; Basko et al., 1974). The reflected component will have characteristics different from the direct radiation (energy spectrum, polarization, etc.) so its inclusion in the model will change the predicted observations at the earth.

The contribution of the reflected component is significant if the electrons are beamed toward the photosphere as in the model developed at Stanford (Petrosian, 1973). In particular for bursts located at the center of the solar disk and at high energies where the x-rays are directed toward the photosphere, the reflected component may dominate the direct radiation.

A Monte Carlo procedure is being developed to find the diffusely reflected spectrum. The results of this method are at present being compared to certain solved problems in diffuse reflection (Chandrasekhar, 1960) to gain familiarity with the number of events that must be generated to gain a desired accuracy. This knowledge will be used to evaluate the results obtained when the procedure is used to predict the properties of the radiation reflected from an appropriate model photosphere.

c) Model of Evolution of Flare Plasma

A simple model has been proposed (Sturrock, 1973) which leads to simple estimates of the temperature and emission measure of flare plasma produced by reconnection in a highly idealized model. Formulas are obtained which relate the temperature, emission measure and lifetime of the flare plasma to the magnetic field strength and to the length of the flux tube under consideration. This model has been further analyzed by Moore and Datlowe (1975), who have extended the model and compared its properties with a large number of flares observed optically by the Big Bear Observatory and, in x-rays, by the UCSD experiment on OSO-7. Their analysis shows that the model agrees well with the data.

This success indicates that it would be profitable to develop the model further. There are theoretical (Sturrock, 1968) and observational (Bruzek, 1974) reasons for expecting that, as a flare evolves, different shells are filled with flare plasma, beginning with small low-lying shells and progressing to large shells high in the corona. We propose to make an analysis of the evolution of a flare in such a magnetic-field configuration, using the same physical assumptions and mechanisms as proposed in the very simple treatment given in the Goddard Symposium (Sturrock, 1973), but developing the analysis to apply to the gradual evolution of a large flare in an extensive magnetic field.

As a further extension of this model, we may consider that the initial energy release goes primarily into an electron stream which gives rise to an impulsive x-ray burst. A given model would then lead to expected time behavior of the hard x-ray emission, of the soft x-ray emission, and possibly the Hα emission if the method of excitation of this radiation can be determined. We see three possibilities: one is that the Hα radiation is due primarily to bombardment of the chromosphere by the initial electron stream; the second possibility is that the radiation is due primarily to heat conduction from the hot thermal plasma; a third possibility is that Hα radiation is due to the excitation of the chromosphere resulting from irradiation by x-rays produced in the coronal flare plasma.

Development of this model along the above lines, and comparison with observational data derived from the OSO-5 experiments and complementary data, will provide a further test of the basic ideas underlying this flare model. If comparison with data justifies the model, we should then be able to extract further information concerning the mechanism of particle acceleration in solar flares.

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